Adaptive Traffic Light Controlling Methodology Using Connected Vehicles Concepts

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Abstract— Despite the fact that they play a major role in organizing traffic flow, traffic lights can sometimes introduce significant delays and cause severe traffic congestion, especially during peak demand hours. However, based on the connected vehicles concepts proposed by USDOT, where vehicles will be able communicate with infrastructure and with other vehicles, adaptive traffic light controlling methodologies should provide the best performance for such ITS applications, and significantly help in reducing waiting times and congestion. Although it has been well studied by many in the research community, adaptive traffic light controlling algorithms have not been widely studied in a V2X-based environment.

In this paper, a methodology for adaptively controlling traffic lights, using V2X exchanged messages, is proposed and evaluated. Compared to a relatively smart pre-timed algorithm, which defines different cycle lengths and phase splitting for different times of the day, the proposed methodology outperforms this pre-timed one for many measures of effectiveness such as control delay introduced by the traffic light, as well as queue length, waiting and traveling times.

1. Introduction

The first four-way, three-state traffic light was invented by police officer "William Potts" in Detroit, Michigan in 1920. Ever since then, traffic lights have been one of the most important means for traffic management. In fact, they have proven during the past century their efficiency in organizing traffic flow, and reducing traffic jams. The concepts of connected intersection control, and automatic traffic lights are as old as the idea itself. The first interconnected traffic signal system was installed in Salt Lake City in 1917, with six connected intersections controlled simultaneously from a manual switch. Automatic control of interconnected traffic lights was introduced March 1922 in Houston, Texas [16]. When the need for intelligent transportation systems arose, traffic lights received a considerable amount of attention, and many approaches to achieve adaptive traffic lights were proposed. These included, but were not limited to, metal detectors and computer vision. However those systems lacked accuracy because they were based on the accuracy of sensors, or the robustness of the computer vision algorithm used. After the connected vehicles concept was proposed, in which every vehicle shares information about its status with other vehicles and infrastructure, a wide range of new possibilities arose, and one of them was adaptive traffic light systems based on accurate real time traffic information collected from the vehicular network.

The problem of real-time adaptive traffic lights has been well covered in the literature with two main streams of interest, one focused on the algorithm used to determine cycle length and green phases timing, regardless of the means used to collect traffic data; while the other focused on introducing new ways of collecting traffic data, with the help of a simple algorithm to present performance evaluation and results. B. Zhou et al. propose an adaptive traffic light control algorithm that uses traffic data collected from a wireless sensor network to determine sequence and length of the traffic light phases [17]. The authors assume the intersection can only be in one of 16 cases, and they use a mathematical model to determine the intersection's next case and the period over which it should persist. On the other hand, D. T Dissanayake et al. propose an algorithm for vehicle detection based on a Magneto-Resistive sensor [18]. Also, K. Al-Khateeb et al. propose a real-time dynamic traffic light sequence determination algorithm, but this time using RFID technology to collect real-time traffic information [19]. Although some of the published research present a relatively easy algorithm to determine traffic light cycle length and phases timing, others present very complicated algorithms that incorporate the learning abilities of artificial neural networks, with the decision making of fuzzy expert systems such as the work presented in [20].

Despite the high level of attention to adaptive traffic light systems, only a few papers considered the connected vehicles concepts (i.e. vehicle-to-vehicle and vehicle-to-infrastructure (V2V/V2I) communications) as the source for the real-time traffic information. M. Ferreira *et al.* present a new concept of traffic management at intersections, using only V2V communications [21]. The proposed algorithm does not require either roadside equipment (RSE), or a traffic light. The algorithm is only based on communication

between vehicles at the same intersection, and the traffic light is replaced with an internal traffic light presented on a display in each vehicle. Another V2V/V2I utilization was presented by V. Gradinescu *et al.*, in which V2V/V2I messages are used to collect real-time information about the traffic conditions around the intersection, and then a simple algorithm based on the well known Webster's equation is used to determine cycle length as well as green time splitting [22].

In this paper, an adaptive traffic light controlling methodology using V2V/V2I communications is proposed and evaluated. Traffic information will be collected from V2V/V2I messages exchanged with cycle length and green times determined using an algorithm based on Webster's equation. The remainder of the chapter is organized as follows, section 2 summarizes the different classifications of traffic light control systems known in the literature; section 3 presents the algorithm used to determine the traffic light's cycle length and green times; section 4 describes the simulation model used in detail; evaluation and validation results are discussed in section 5; and a conclusion along with future possible work puts this chapter to an end in section 6.

2. Classification of Traffic Light Controlling Systems

A traffic light can be defined by three major elements which are, cycle length, green time splits, and relation to the surrounding environment. Accordingly, traffic lights can be classified into three main categories: pretimed, actuated and adaptive.

In pretimed traffic lights, cycle length and green time splits are pre-determined before the traffic light is put to operation. In addition, the traffic light does not respond to any sudden changes in the surrounding environment. This is the most basic and simple form of a traffic light. Further enhancements were done by defining different programs (cycle length and green times) for different times of the day, or day of the week. Historical data about traffic flow were used to find peak hours and assign suitable cycle length and green times accordingly.

Actuated traffic lights form an enhanced version of pretimed traffic lights. In actuated traffic lights, cycle length and green times are pre-timed, however the traffic light's ability to respond to surrounding environment events is introduced by adding sensors on some, or all, the controlled roads by that traffic light. Thus the main difference between pretimed and actuated is the ability to respond to some events from the surrounding environment. For example, in an intersection comprised of a major road crossed by a secondary road, an actuated traffic light can be used to



Fig. 1: Different Categories of Adaptive Traffic Lights

extend green on the main road as long as no traffic is present at the secondary road; in case of incoming traffic on both directions, the traffic light will work based on the pretimed program previously defined for that time of the day and the day of the week.

The third category of traffic lights is the adaptive one, in which cycle length and green times are calculated based on traffic data collected in a real-time manner from the surrounding environment. Several sub-categories can be defined based on traffic data collection technique, and the algorithm used to calculate different parameters and assign green and red lights. Figure 1 shows the different sub-categories of adaptive traffic lights based on data collection technique and data processing algorithm.

3. Algorithm

Algorithms for controlling adaptive traffic lights can be simple (simple mathematical model), or very complicated (combination of fuzzy logic and artificial neural networks). Webster's equation is a tool used to determine the optimal cycle length for a traffic light according to traffic flow information and lost times such as yellow times and allred times. Traffic flow information is usually taken from historical data and fed into the equation. However, since vehicles can communicate with each other and with the infrastructure using V2V/V2I communications, the data can be collected from the incoming vehicles themselves, and can be fed into the equation to come up with an optimized cycle length and green times for the current situation which will result in optimized performance and increased throughput of the controlled intersection. Equation 1 shows Webster's equation in which demand levels are represented by a factor called critical flow ratio which is the ratio of the current flow rate captured from the exchanged messages, over the road's saturation flow rate.

$$C_0 = \frac{1.5 \cdot L + 5}{1 - \sum_{i=1}^{i=n} y^i}$$
(1)

where: C_0 is optimal cycle length [sec], L is lost times (yellow + all-red) [sec], y^i is critical ratio of road segment group i, and n is number of road segment groups; where the road segment group is the group of road segment on which

incoming flow can access the intersection simultaneously.

The idea is to calculate cycle length and green times splits every new cycle so the system can dynamically adapt to changes in the input traffic flow. This algorithm uses information from messages exchanged between vehicles, those messages contain information about the vehicle's position, speed, acceleration, and many different parameters. Since these messages are received in every simulation step, a special procedure for accumulating the information over a complete cycle length is needed. For that, a procedure from one of the published papers was imported and used here. The procedure is proposed by S.-F. Cheng *et al.*, and can be found in the appendix of their published paper about an algorithm for coordinated traffic lights [23].

The procedure calculates—for each road segment group the estimated flow as follows:

$$v^i = f^i + 4q^i \tag{2}$$

where v^i is the estimated flow for road segment group i, f^i is the exponentially smoothed average incoming flow on road segment group i, and q^i is the exponentially smoothed average size of the standing queue on road segment group i.

Both average incoming flow (f^i) and average size of the standing queue (q^i) of road segment group *i* are obtained by periodically performing the following exponential smoothing updates:

$$f^i := 0.75 f^i + 0.25 f^i_{in} \tag{3}$$

$$q^i := 0.9q^i + 0.1\hat{q}^i \tag{4}$$

where f_{in}^i is the number of vehicles flowing into road segment group *i* during the interval between smoothing updates (one simulation step), and \hat{q}^i is the size of standing queue on road segment group *i* during the same interval.

Then the critical flow ratios are calculated. Those values are used as a measure to represent the relative congestion of each road segment group, and thus help in the calculation of cycle length and green times. Critical flow ratios are calculated—for road segment group i—as the ratio between the estimated flow and the saturation flow rate:

$$y^{i} = \frac{v^{i}}{m \times s^{i}} \tag{5}$$

where v^i is the estimated flow calculated in equation (2), s^i is the saturation flow rate of one road segment, and m is the number of road segments inside of a road segment group i.

In order to use Webster's equation to calculate cycle length, a final parameter must be defined, which is lost times. For this work, lost times are only limited to yellow times. There are two yellow phases for the considered intersection. To determine the time in each of those yellow phases, a well known rule in traffic design was used. This rule determines yellow time for an approach of an intersection (in seconds) according to the speed limit(in miles per hour (mph)) on that approach. According to this rule, 1 second of yellow time should be scheduled for every 10 mph in the maximum speed allowed. In our design (explained later in section 4), the speed limit on all approaches is 40 mph, and thus one phase of yellow time is 4 sec. In conclusion, L in Webster's equation will be replaced by 8 seconds.

Now Webster's equation can be used to calculate the optimal cycle length C_0 according to the estimated flows. Also green times can be calculated according to critical ratios calculated in equation (5) as follows:

$$g^i = \frac{y^i}{Y}(C_0 - L) \tag{6}$$

where g^i is the green time that should be associated with the road segment group *i*.

Some limitations should be introduced to the algorithm to ensure the optimal result. For example, minimum green time, which is the minimum amount of time required by a pedestrian to cross the road segment with an average speed 4ft/s should be respected. Also, a minimum and a maximum cycle length should be respected, where the minimum cycle length is the sum of two minimal green times with two yellow times, and the maximum cycle length is normally $1.5 C_0$ for a C_0 calculated in moderate conditions.

The algorithm has also been extended to deal with special traffic cases. There are two cases that are covered by the programmed algorithm and those are: a) eliminating tedious waiting times on red by switching the traffic light automatically to green when the opposite direction has no demand; and b) extending a finished green phase when the opposite direction has no demand.

4. Simulation Model Design

The simulation scenario that will be used to validate the concept needs to be as realistic as possible. To build such a scenario, the following parts of the scenario should be addressed and defined carefully: a) the road network; b) traffic flows that will run through the network; and c) the routing algorithm used to route vehicles between their respective origin and destination. Since this simulation scenario will be targeting the evaluation of the performance of adaptive traffic light controlling algorithms, only a single intersection is needed, and thus routing will not have an essential role in the evaluation process.

The road network consists of an isolated 4-way intersection, with each approach having two directions, as



Fig. 2: Proposed Intersection

illustrated in Figure 2. Since similar work had been done in the literature by V. Gradinescu *et al.* [22], we tried to reproduce their model and thus acquire the opportunity to validate our simulation by comparing both results. However, in their paper, the model used was not fully specified. They provided the shape of the intersection, number of lanes and input flow rates on each approach, but the model lacked detailed description of the intersection such as left/right turns, speed limit on different approaches, vehicle-based parameters (max speed, acceleration, deceleration, length), the distribution of different types of vehicles, and the pre-timed cycle length and green times of the traffic light controlling the intersection. In other words, many elements that define the simulation scenario were unspecified, and thus it is not possible to compare both results.

The road network used for this scenario is an isolated 4way intersection—and by *isolated* we mean that the effect of adjacent intersections was not considered—with each approach having two directions, and with each direction having three lanes. No left or right turns are allowed at the intersection. The speed limit on all lanes is 40 mph \approx 17.89 m/s. Vehicles participating in the scenario were assumed to be of four types: *Typical*, *Fast*, *Slow* and *Van*, Table 1 specifies the different parameters and distribution for each vehicle type.

Input flow of vehicles into the intersection should be defined very carefully to represent situations such as peak hour demand. For this evaluation process, the used input flow definition was inspired by the one used by V. Gradinescu *et al.* in [22]. It assumes the simulation covers almost three hours of real life, during which a peak demand will occur. This helps in understanding the performance of the evaluated algorithm in different demand levels. The input flow on different approaches and their variations over the simulation

Table 1: Vehicles Types in the simulation

| Veh Ty | icle pe | Max Speed [m/s] | Acceleration [m/s ²] | Length [m] | Probability [%] |
|----------------|------------|--------------------|----------------------------------|------------|--------------------|
| Тур | ical | 70 | 2.68 | 7.5 | 49 |
| Fa | ist | 80 | 3.83 | 7 | 19 |
| Slow | | 60 | 1.92 | 6.5 | 22 |
| Va | an | 60 | 2.44 | 10 | 10 |
| 2500 = 2000 | | | | | |
| 1500 | | | | | South |
| 0 | | 50 | Simulation Time [min] | 100 | 1: |

Fig. 3: Incoming Flow over Simualtion Time for all scenarios

time are illustrated in Figure 3.

The pre-timed traffic light cycle definition used is the one generated by default by SUMO. It gives 31 simulation seconds to each approach as green time and 4 simulation seconds as yellow time.

5. Evaluation and Validation

The simulation scenario simulates three hours of real life during which a peak demand will occur, and then the demand will go down to a normal level. The measure of effectiveness (MOE) used to evaluate the performance of the algorithm is basically the *average control delay* which is a widely used MOE for the evaluation of traffic light controlling algorithms, and it is defined as the difference in travel time for vehicles when travelling down a road with the traffic light controlling that road and when there is no traffic light controlling that road.

As illustrated in Figure 4, the simulation shows that the used algorithm outperforms the pre-timed traffic light over the entire simulation time. In addition, the algorithm improves the recovery time of the intersection after a the peak demand.



Fig. 4: Average Control Delay for the algorithm compared to that of conventional pre-timed control



Fig. 5: Average Control Delay for the algorithm compared with a "smart" pre-timed control

Moreover, after evaluating different cycle lengths for the pre-timed program, it was noticed that long cycle lengths are suitable for high demand situations, and short cycle lengths are suitable for low demand periods, thus a smart pre-timed program was evaluated. The traffic light starts with a short cycle length (60 min) up to minute 25 were it switches to a longer cycle length (80 min) with a fixed yellow times. Then, when the simulation reaches minute 55, the traffic light switches back to the old timing. The results for this smart pre-timed program are shown in Figure 5. The adaptive algorithm used outperforms the "smart" pre-timed program and provides lower control delays over the entire simulation time.

Other MOEs have been evaluated such as queue length, waiting time, travel time, and reductions in emissions and fuel consumption.

Figure 6 shows the results of evaluating queue length in front of the traffic light. Although the adaptive algorithm increased queue length on northbound lanes during a portion of the peak demand period, the algorithm succeeded in reducing queue length in front of the traffic light over the entire simulation time. This indicates that the adaptive algorithm has succeeded in reducing congestion at the intersection.

In terms of waiting and travel time, the adaptive algorithm improves the over all performance although small delays are introduced on northbound lanes while reducing them on eastbound lanes. Figures 7 and 8 show the simulation results of evaluating those parameters on every bound.

6. Conclusion

In this paper, a methodology for adaptively controlling traffic lights in a connected vehicles environment was proposed and evaluated.

The algorithm was based on the well-known Webster's equation, which determines the optimal cycle length and green times based on the demand level in each direction. The algorithm used messages exchanged between the vehicles and the traffic light (V2I) to estimate demand level and thus calculate a suitable cycle length and green times splits. Many parameters were considered in the algorithm such as minimum and maximum cycle length, and minimum green time for one direction. Also, the algorithm was able to

react to special event at the intersection such as switching the traffic light to green for a direction waiting on red while there is no demand on the opposite direction, and extending the green phase beyond the calculated value for one direction as long as the opposite direction has no demand while respecting maximum acceptable waiting times for pedestrians.

iTETRIS, the open source simulation platform, was used to simulate the algorithm. The simulation scenario was three hours long. By the end of the first hour, the demand on the intersection reaches a peak level, and then gradually decreases back to a low level. The evaluation proved that the proposed algorithm outperformed simple and smart pre-timed controlling algorithms. Average control delay which is a widely used MOE for evaluating traffic light performance—was mainly used to compare the proposed adaptive algorithm with the pre-timed examples, and the comparison showed that the adaptive algorithm succeeded in reducing average control delay, and even enhancing recovery time after the event of a peak demand. Further MOEs were evaluated such as queue length, waiting and travel time, and results show improvement in all of them.

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Fig. 6: Queue Length variations in front of the intersection on all bounds



Fig. 7: Waiting Time variations over simulation time on all bounds



Fig. 8: Travel Time variations over simulation time on all bounds

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